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ABSTRACT

The Eclypse ESP standing wave reflectometer was tested for its ability to locate open and short circuits on pairs of electrical wires. The robust and simple to use hand-held device was shown to operate successfully and quickly on coaxial cables, twisted pairs, shielded cables and pairs of wires within multi-wire looms. For aircraft wire management this offers an improved fault location capability prior to repairs on the flight line or during maintenance. The ESP could also find application in other defence platforms with complex electrical wiring.

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Executive Summary (U)

The incidence of faults in the wiring of aircraft is a persistent problem which causes equipment failure and can endanger the life of the platform and its occupants. The Eclypse ESP standing wave reflectometer has been evaluated for its ability to find the location of a short circuit or an open circuit on a pair of wires. An open circuit occurs when a wire breaks and interrupts the connection to the equipment. A short circuit occurs when insulation damage allows the conductors to touch. While the existence of such faults can be readily determined, its location is often difficult to ascertain due to the complexity of aircraft wiring and the fact that the wiring is often inaccessible or hidden within multi-wire looms. A modern aircraft contains some tens of kilometres of wiring and so an aid to wire fault location is highly desirable. Further, aircraft wiring is susceptible to damage from handling and hence any unnecessary disruption of installed wire needs to be avoided. The Eclypse ESP exploits the fact that in many cases the cables are electromagnetic transmission lines which propagate high frequency electrical signals. In the case of coaxial cables and twisted pairs this is intentional as they are designed to transfer signals of this type between avionics equipment. In the case of wires bundled together in a loom the formation of a transmission line is incidental. In both cases the device utilises the fact that a short circuit or an open circuit on a transmission line is a point of reflection for a signal injected by the device. By transmitting signals over a frequency range the device can determine the type of fault and its distance along the wires. Testing in the laboratory showed it to be capable of detecting wire faults in coaxial cables, shielded cable, twisted pairs and a pair of wires in a loom.

Contents

1. Introduction

Electrical wiring for aircraft is susceptible to a number of failure modes. In many cases the electrical conductors can break causing an open circuit. On other occasions the electrical insulation protecting the electrical conductor can wear away or crack and so allow for the possibility of an electrical short circuit. The large amount of wiring in a modern aircraft can amount to several tens of kilometres in length making the location of short circuits and open circuits a tedious problem. One means of finding the location of these types of faults is to use a standing wave reflectometer.

The National Aeronautics and Space Administration (NASA) at Kennedy Space Center developed the standing wave reflectometer [1] to aid in the detection of short circuits and open circuits on its Space Shuttle Orbiters. The advantage of the standing wave reflectometer over existing time domain reflectometers is its ability to detect faults at shorter distances. The standing wave reflectometer underwent commercial development at Eclypse International located at Corona, California USA where it is marketed as the ESP standing wave reflectometer. This instrument was purchased by DSTO and tested in the laboratory as part of a program aimed at improving aircraft wire maintenance.

2. Background

2.1 Operating Principles

A standing wave reflectometer utilises the signal reflected from a discontinuity such as a short or open circuit in a transmission line to determine the distance from the measuring point to the discontinuity. The transmission line may be intentional such as for a coaxial cable or incidental as for a wire bundle. The standing wave reflectometer is connected to two conductors at one end on the cable to be tested. A schematic diagram is shown in Figure 1 in which the transmission line has a length L, is connected to the reflectometer at z=0 and to a load at z=L. The load, $\hat{Z}_L$ simulates the fault condition at the end of the transmission line, with a numerical value of 0 for a short circuit and a value of ∞ for an open circuit. The characteristic impedance of the transmission line is $\hat{Z}_0$. The reflectometer has an input impedance of $\hat{Z}_S$ and injects a continuous wave narrow band signal $V_S \cos \omega t$ to the line. Two stable signals are formed on the line: (*i*), $\hat{V}^+(z)$ travelling from left to right and (*ii*), $\hat{V}^-(z)$ travelling from right to left after reflection at the load $\hat{Z}_L$. Each parameter with a caret (i.e. $\hat{V}^+(z)$), denotes a phasor representation.

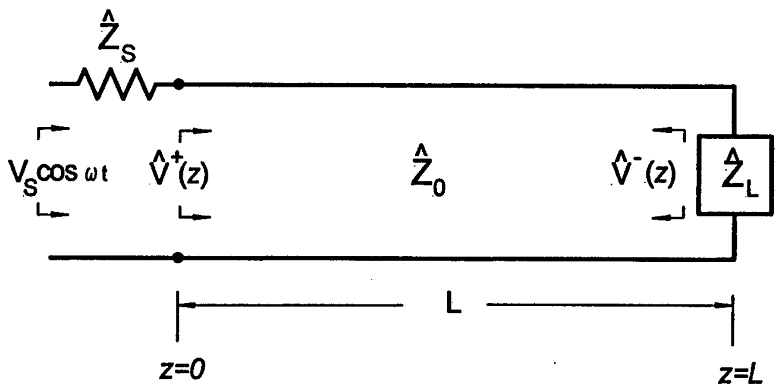

Figure 1. Transmission line with signal, input load and termination load.

The reflected signal is a function of the load and characteristic impedances. At the load this value, termed the reflection coefficient $\hat{\Gamma}_L$ is represented as

$$\hat{\Gamma}_L = \frac{\hat{Z}_L - \hat{Z}_0}{\hat{Z}_L + \hat{Z}_0} \tag{1}$$

The nature of the reflection behaviour at the load can readily be seen by a simple investigation of this equation. If the value for a short circuit, namely zero, is substituted for $\hat{Z}_L$ the reflection coefficient is seen to be minus one. This means that the reflected voltage at the load is equal in magnitude but with an opposite sign to that of the incident signal. If a very large value is substituted for $\hat{Z}_L$ then the value of the characteristic impedance in the equation becomes insignificant and the reflected voltage at the load is now equal in magnitude and sign to the incident signal. In the case of the load being matched to the characteristic impedance of the line the reflection coefficient is zero and there is no reflected signal. In general the values vary along the length of the transmission line in a way that is determined by the velocity (or the related wavelength, frequency and phase constant) of the waves. In line with normal practice the phase constant β for the wave in the transmission line will be used with

$$\beta = \frac{2\pi f}{v} = \frac{2\pi f}{v_r c} = \frac{2\pi}{\lambda} \tag{2}$$

where

f is the frequency of the signal
λ is the wavelength of the signal
v is the velocity of the wave
v_r is the relative velocity of the wave
c is the velocity of light in a vacuum

The voltage of combined signals can be represented at any point along the transmission line. The reflectometer is connected at the source end so has access to the signal at z=0.

It is this signal that is used to determine the type of discontinuity and distance along the line where it occurs. The relationship for voltage [2] at z=0 is

$$\hat{V}(0) = \left[\frac{1+\hat{\Gamma}_L e^{-j2\beta L}}{1-\hat{\Gamma}_S\hat{\Gamma}_L e^{-j2\beta L}}\right]\left(\frac{\hat{Z}_0}{\hat{Z}_S+\hat{Z}_0}\right)V_S \tag{3}$$

It can be seen that a mismatch between the source impedance and the transmission line produces its own reflections. Accordingly it is a preferred practice to match the input impedance and the transmission line with the same impedance so that $\hat{Z}_S = \hat{Z}_0$ and $\hat{\Gamma}_S = 0$ in which case the relation simplifies to

$$\hat{V}(0) = \frac{1}{2}\left[1+\hat{\Gamma}_L e^{-j\beta L}\right]V_S \tag{4}$$

It can be seen that the effect of the matched source impedance is to introduce the factor of a half between the signal generated by the device and the signal at the start of the line. This means that half the signal from the device occurs across the source impedance in this case. It is often more convenient to consider the relation in terms of the signal in the line only so that the half factor can be ignored. The voltage at the input for the reflectometer is shown in Figure 2 for a length of transmission line with five load impedances of 0 Ω, ∞ Ω, 35 Ω, 50 Ω and 75 Ω. The length of line is 14.8 m, it has a relative velocity of 0.66 and a characteristic impedance of 50 Ω. The frequency range of the calculation is from 200 kHz to 10 MHz. For the transmission line terminated in a load of 50 Ω, there is no reflected signal, only the injected signal is measured and so the value is one for all injected frequencies. For an open circuit the reflection coefficient is one, and so when the wavelength is large compared to the length of the line a reflected signal equal to the injected signal occurs at the input. Added together this results in a voltage twice the input voltage. For a short circuit, the reflection coefficient is minus one so that for a wavelength large compared to the length of the line, a signal equal to the input signal but with opposite sign will appear at the input. Added together this results in a combined signal of zero. Other non matched signals will give responses in between that of the extremes of a short circuit or an open circuit for the same frequency conditions.

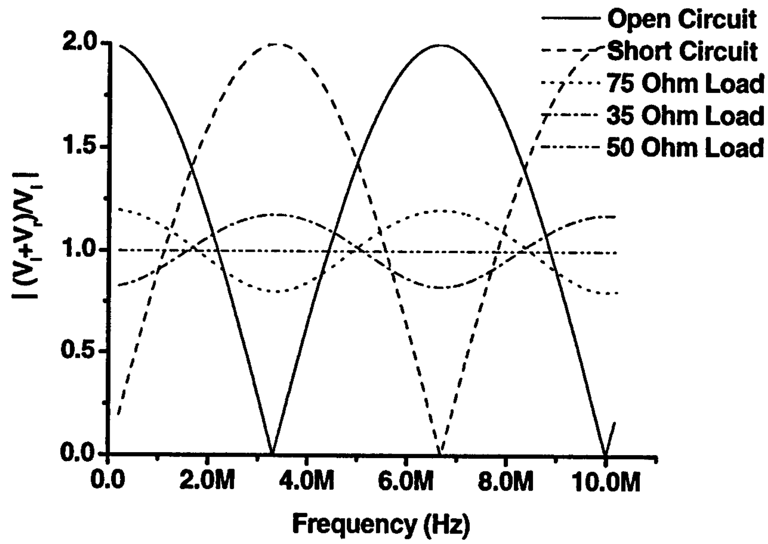

Figure 2. Plots showing the relative combined potential magnitudes at a SWR measuring a 14.8 m cable with a relative velocity of 0.66 for five selected loads.

As the frequency increases from an initial low value, the magnitude of the voltage at the input of the transmission line increases if it is terminated with loads less than the characteristic impedance and decreases if it is terminated with loads greater than the characteristic impedance. In each case a minimum is reached. To find the minimum, equation (4) can be changed to

$$\frac{\hat{V}(0)}{V} = \frac{1}{2}\left[1 + \hat{\Gamma}_L Cos 2\beta L\right] = 0 \qquad (5)$$

The value of the minimum depends on whether the reflection coefficient $\hat{\Gamma}_L$ is positive or negative. If the reflection coefficient is positive as for an open circuit the first minimum occurs when the relationship between L_{oc} and the wavelength of the signal λ_{oc} satisfies

$$L_{oc} = \frac{\lambda_{oc}}{4} \qquad (6)$$

If the reflection coefficient is negative as for a short circuit, the first minimum occurs when the relationship between L_{sc} and the wavelength λ_{sc} of the signal satisfies the equation

$$L_{sc} = \frac{\lambda_{sc}}{2} \qquad (7)$$

2.2 Wire Parameters

Using the electrical constitutive parameters of permittivity ε, and permeability μ for the insulator and a geometric factor, *F* for the conductors the characteristic impedance, Z_0 of a transmission line can be expressed as

$$Z_0 = \sqrt{\frac{\mu}{\varepsilon}} \times F \qquad (8)$$

with $\varepsilon = \varepsilon_0 \times \varepsilon_r$ and $\mu = \mu_0 \times \mu_r$

The value for the geometric function depends on the configuration of the wires and the physical size. While the geometric functions are often provided in texts on transmission lines, the value for the characteristic impedance for an intentional transmission line is usually freely known and often written on the outer jacket. The characteristic impedance is usually in the range of 50 to 300 Ω.

The relative permeability, μ_r of insulators used on electrical wires is usually equal to one, so the effective permeability is that of free space μ_0. The relative permittivity, ε_r of insulators is typically in the range of 1.5 to 3.5 for polymers. In the case of an air insulator the permittivity of free space, ε_0 applies.

The velocity, v of the wave in the transmission line is given by

$$v = \frac{1}{\sqrt{\varepsilon\mu}} \qquad (9)$$

The velocity of signal in a transmission line is often stated as a ratio compared to the speed of light in a vacuum, c for which μ_r and ε_r are equal to one. The speed of the wave in a vacuum is approximately 300 Mm s^{-1}. Since the relative permeability of insulating materials is almost always equal to one, the relative velocity is a function of relative permittivity only. The relative velocity is usually in the range 0.45 to 0.8 and its value, v_r can be determined in terms of the relative permittivity, ε_r of the insulating material by

$$v_r = \frac{1}{\sqrt{\varepsilon_r}} \qquad (10)$$

The relative velocity is quoted for intentional transmission lines as part of the manufacturer's specifications. For unintentional transmission lines knowledge of the relative permittivity, sometimes called the dielectric constant, of the insulator provides the means for evaluating the relative velocity using (10). The relative permittivity for polyethylene for example is 2.3 giving a relative velocity of 0.66 which corresponds to that for the example used in Figure 2.

2.3 Operating Characteristics

Characteristic impedance values can be input to the device within the range 20 – 400 Ω in 1 Ω intervals. The relative velocity can be varied in increments of 0.001 within the range 0.200 – 1.000. The maximum length to a fault the device can detect is 1000 feet (305 m) [3]. The minimum range for an open circuit is 0 feet (0 m) and 4 feet (1.2 m) for a short circuit. Accuracy is quoted as ± 0.75 %.

The device operates on 6 V rechargeable batteries and is supplied with a battery charger. It is estimated that the batteries can provide 40 hr of use on a 35 % duty cycle. The output signal has a maximum level of 2 V peak to peak. The frequencies used for distance measurement are quoted in the patent for the device as being in the range 10 kHz to 50 MHz. For testing, connection is made through a BNC connector direct to the body of the standing wave reflectometer or to two clips on a lead breakout from a 75 Ω coaxial cable.

To accommodate various cable types, the standing wave reflectometer requires a characteristic impedance and a relative velocity value to be set. The characteristic impedance is used to adjust for the discontinuity produced by the device input impedance, $\hat{Z}_S$ (see Equation 3) at the connection of device to the cable under test. The relative velocity factor is equivalent to v_r in Equation (10) and this allows (by multiplication with c, the velocity of light in a vacuum) the evaluation of v the absolute velocity of the wave in the transmission line. Equation (2) enables the effective wavelength in the transmission line to be calculated and hence distance measuring Equations (6 & 7) can be applied. The values can be either default values, input directly from the keyboard, chosen from one of four preset coaxial cable types or chosen from user set types.

2.4 Operating Limitations

The handbook [3] notes as an application hint that distance results displayed by the ESP are dependent upon the set value of relative velocity. These values can be obtained from standards and data sheets for intentional transmission lines such as coaxial cables and twisted pairs although they may be temperature sensitive. For incidental transmission lines such as wire pairs in a bundle of many wires, the value will need to be estimated.

The setting of the characteristic impedance is less critical. However the handbook [3] notes that the mismatched impedance between the device and the connection to the cable under test can also cause location errors in the range of 5 % in extreme cases.

The structure of cable under test will influence the results of the ESP standing wave reflectometer. The preferred cable structures listed in descending order of preference are:

a. Coaxial or single shielded conductors;
b. Pairs of wires within a shield;
c. One of a pair to a shield;
d. Twisted pair unshielded;
e. Adjacent wires unshielded;
f. Wires in the same bundle and
g. A wire to a metal structure.

3. Measurements

3.1 Method

The ESP standing wave reflectometer was tested against known lengths of cable, which were either open circuited or short circuited. The types of cable tested were:

a. Coaxial cable;
b. 3 wire shielded cable;
c. Twisted pair (no shield) and
d. Wires in the same loom.

In the case of the coaxial cable, tests were also performed while the cable was terminated by a resistance equal to the characteristic impedance.

3.2 Measurements on Coaxial Cable

Two lengths of RG-58 C/U cable were tested. The first cable tested contained the description on the outside jacket which read, Belden 8262 M17/155-00001 MIL-C-1716428 LL 7824 CSA CXC PR. The second cable contained the description on its jacket which read, ASC R3058 RG58 Type.

The Belden coaxial cable contained BNC connectors at each end and was directly connected at one end to the BNC connector on the body of the standing wave reflectometer. The cable was tested with short circuit, open circuit and while terminated with a load equal to its characteristic impedance (matched load). The short circuit and termination loads were both in the form of BNC end terminators. For the open circuit tests the BNC connector at the remote end was left unconnected. The ASC (Austral Standard Cables) cable was wound onto a metal reel and was fitted with a BNC connector at one end. The shield at the other end was stripped back 15 mm and wound into a "pigtail" while the insulation on the central conductor was stripped back by 5 mm.

For RG-58 cable the nominal characteristic impedance is 50 Ω and the relative velocity is 0.66. The ESP standing wave reflectometer has preset values for RG-58 cable set at 53 Ω and 0.695.

Measurements on the Belden cable are shown in Table 1. The length of the cable was measured separately at 2.975 m. In the first column the nature of the termination is shown. The second column shows the diagnosis of the cable termination as displayed

by the standing wave reflectometer. Column three contains the length to termination measured in imperial units while the fourth column gives the same result in metres. The length adjusted to reflect the standard relative velocity is given in the fifth column. The final column shows the percentage error.

Table 1. Test results for a Belden RG 58 cable of length 2.975 m.

Termination	Detected Termination	Length Detected (Foot.inch)	(metre)	Adjusted Length (metre)	Error %
Open Circuit	Open Detected	10.8	3.25	3.09	3.8
Open Circuit	Open Detected	10.8	3.25	3.09	3.8
Open Circuit	Open Detected	10.8	3.25	3.09	3.8
Short Circuit	Short Detected	10.9	3.28	3.11	4.6
Short Circuit	Short Detected	10.9	3.28	3.11	4.6
Short Circuit	Short Detected	10.9	3.28	3.11	4.6
Matched (50 Ω)	Open Detected	34.8	10.57	10.03	-
Matched (50 Ω)	Open Detected	413.3	126.0	119.6	-
Matched (50 Ω)	Open Detected	413.3	126.0	119.6	-
Matched (50 Ω)	No Faults Found	-	-	-	-
Matched (50 Ω)	No Faults Found	-	-	-	-
Matched (50 Ω)	No Faults Found	-	-	-	-
Matched (50 Ω)	No Faults Found	-	-	-	-

Due to the unreliable results for the first set of measurements on the Belden cable with a matched load this test was repeated fifty times. On twenty five occasions the standing wave reflectometer correctly detected the cable to have no faults found. On the other occasions an open circuit was detected with a distance measurement that varied randomly between 34 feet (10.4 m) and 3069 feet 10 inches (935.68 m).

The results on the ASC cable are shown in Table 2. In this instance the cable was not tested for a matched load, since the remote end did not contain a connector. A short circuit was produced in this cable by winding the "pigtail" made by exposed shielding around the exposed conductor.

Table 2. Test results for ASC RG 58 cable of length 86.50 m. The standing wave reflectometer was connected directly to the single BNC on the cable.

Termination	Detected Termination	Length Detected (Foot.inch)	(metre)	Adjusted Length (metre)	Error %
Open Circuit	Open Detected	302.9	92.28	87.63	1.3
Short Circuit	Short Detected	302.4	92.15	87.51	1.2

The tests for the ASC cable were carried out with the standing wave reflectometer connected to the end with exposed wires via the breakout wires and clips. A BNC female-to-female adapter was added to the fitted connector to facilitate adding the

short circuit and matched loads. This added approximately 2 inches to the readings. The length of the breakout wire pair is 200 mm. The results are shown in Table 3.

Table 3. Test results for ASC RG 58 cable of length 86.50 m. The standing wave reflectometer was connected to exposed shield and centre conductor via breakout leads and clips of length 200 mm.

Termination	Detected Termination	Length Detected (Foot.inch)	(metre)	Adjusted Length (metre)	Error %
Open Circuit	Open Detected	305.2	93.02	88.33	2.1
Short Circuit	Short Detected	304.11	92.94	88.26	2.0

Inconsistent results were obtained for the ASC cable terminated with a matched load while connected via the breakout cable. The test was repeated fifty times with the display showing no faults found on seven occasions. A summary of the results is given in Table 4.

Table 4. Test results for ASC RG 58 cable of length 86.50 m with matched termination. The standing wave reflectometer was connected to the shield and centre conductor via breakout leads and clips of length 200 mm.

Termination	Detected Termination	Length Detected (Foot.inch)	(m)	Number of Readings
Matched (50 Ω)	Open Detected	157.7 to 158.0	48.03 to 48.16	17
Matched (50 Ω)	Open Detected	169.4 to 169.11	51.61 to 51.79	24
Matched (50 Ω)	Open Detected	3092.10	942.70	1
Matched (50 Ω)	Open Detected	3234.10	985.98	1
Matched (50 Ω)	No Faults Found	-	-	7

3.3 Measurements on 3-wire Shielded Cable

Measurements were carried out on a 3-wire shielded cable on a loom removed from the leading edge of a C130E aircraft wing. The cable was marked M27500-20 ML3T08-6090. This corresponds to a cable with three 20 Gauge Mil-W-81044 cross-linked polyalkene insulated, tin coated wires within a shield constructed from round tin-coated wire. The cable was removed as part of a bundle while maintaining its connection to a terminal post and thence to another shielded cable marked 2TN2B20. The shields were electrically connected at a fourth terminal post from a circumferential termination near the end of each cable with approximately 100 mm lengths of wire. Likewise approximately the same lengths of wire protruded outside the shield to make the connection to each terminal post making for a total of 200 mm of wire outside the respective shields. A schematic is shown in Figure 3. The length of the first cable was 3.84 m while the second was 0.65 m, making a total of 4.49 m.

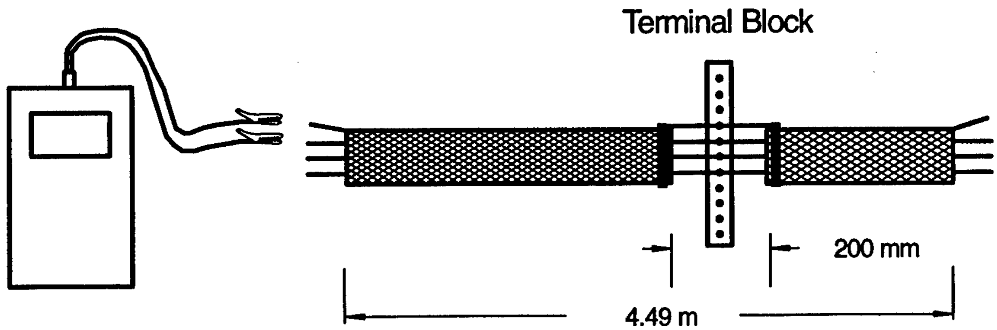

Figure 3 Schematic for test with three wire shielded cable. The test was carried out along two cables connected at a terminal block.

Tests were carried out using the standing wave reflectometer connected to the longer cable both between two individual wires and between one wire and the shield. The results for connections between two wires in the cable are shown in Table 5 for open and closed circuit terminations at the far end of the combined cables. The test was repeated for five characteristic impedance settings on the standing wave reflectometer. The relative velocity was set at 0.45, within the range of 0.45 – 0.48 suggested in the Operating Guide [3] for a wire to wire measurement in a two wire shielded cable. To obtain the length obtained by physical measurement a relative velocity slightly outside this range, namely 0.51 would be required.

The standing wave reflectometer failed to detect the open circuit when its impedance setting was 50 Ω and failed to detect a short circuit when its impedance setting was 20 Ω and 50 Ω. Errors predicted by the device impedance $\hat{Z}_S$ as depicted in Equation (3) would appear to be the cause of the apparent malfunction as the error only occurred for low load values. It would appear that the characteristic impedance of the two wires is significantly higher than 50 Ω.

Table 5. Tests for the standing wave reflectometer connected to two wires of two lengths of cable containing three wires within a shield. Total length of the cables was 4.49 m. Relative velocity setting was 0.45.

Impedance Setting (Ω)	Termination	Detected Termination	Length to Termination (Foot.inch)	(m)
20	Open Circuit	No Fault Found	-	-
50	Open Circuit	Open Circuit	13.0	3.96
100	Open Circuit	Open Circuit	13.0	3.96
200	Open Circuit	Open Circuit	13.0	3.96
400	Open Circuit	Open Circuit	12.11	3.94
20	Short Circuit	No Fault Found	-	-
50	Short Circuit	No Fault Found	-	-
100	Short Circuit	Short Circuit	13.1	3.99
200	Short Circuit	Short Circuit	13.1	3.99
400	Short Circuit	Short Circuit	13.0	3.96

Tests were carried out on the standing wave reflectometer connected to one wire and the shield of the longer cable for open circuit and short circuit termination. The test was carried out at five characteristic impedance settings for the tester and a relative velocity of 0.45. The results are shown in Table 6. The readings were all larger than the corresponding readings for the tester connected to two inner wires. The open circuit was detected for all settings of characteristic impedance. The length reading was consistent for all open circuit readings except for those with the characteristic impedance set at 400 Ω for which the readings were both larger and variable. More accurate length measurements would have been obtained if the relative velocity were increased to 0.49.

Table 6. Tests for the standing wave reflectometer connected to one wire and the shield of two lengths of cable containing three wires within a shield. Total length of the cables was 4.49 m. Relative velocity setting was 0.45.

Impedance Setting (Ω)	Termination	Detected Termination	Length to Termination (Foot.inch)	(m)
20	Open Circuit	Open Circuit	13.8	4.17
50	Open Circuit	Open Circuit	13.8	4.17
100	Open Circuit	Open Circuit	13.8	4.17
200	Open Circuit	Open Circuit	13.8	4.17
400	Open Circuit	Open Circuit	15.2± 0.3	4.62± 0.08
20	Short Circuit	No Fault Found	-	-
50	Short Circuit	No Fault Found	-	-
100	Short Circuit	Short Circuit	13.6	4.11
200	Short Circuit	Short Circuit	13.6	4.11
400	Short Circuit	Short Circuit	13.5	4.09

Standing wave reflectometer tests were carried out on the longer cable after it was separated from the rest of the wire bundle. For consistency the same conditions were applied as for the case when it was attached to the terminal posts and the shorter cable. The results of this test are contained in Table 7 for the wire to wire measurement and Table 8 for the wire to shield measurement.

The wire to wire measurement was less than the corresponding measurement for the cable while connected to a second wire via the terminal posts. The measurements accurately reflected the length of the cable for the open circuit configuration when the standing wave reflectometer had a relative velocity setting of 0.45 and impedance settings in the range of 50 - 400 Ω. For the short circuit configuration correct length measurements to the short circuit were obtained for a narrower range of impedance settings, namely 100 - 400 Ω.

An anomaly was apparent between the readings for the individual cable and the connected cables whereby the latter measurement appeared to be too small. This was likely to have arisen from the change in both characteristic impedance and relative velocity at the point where the wires broke out of the shield and connected to the terminal post.

Table 7. Tests for the standing wave reflectometer connected to two wires within a cable comprising three wires within a shield. Length of the cable was 3.84 m. Relative velocity setting was 0.45.

Impedance Setting (Ω)	Termination	Detected Termination	Length to Termination (Foot.inch)	(m)
20	Open Circuit	No Fault Found	-	-
50	Open Circuit	Open Circuit	12.7	3.83
100	Open Circuit	Open Circuit	12.7	3.83
200	Open Circuit	Open Circuit	12.7	3.83
400	Open Circuit	Open Circuit	11.11	3.63
20	Short Circuit	No Fault Found	-	-
50	Short Circuit	No Fault Found	-	-
100	Short Circuit	Short Circuit	12.9	3.89
200	Short Circuit	Short Circuit	12.9	3.89
400	Short Circuit	Short Circuit	12.9	3.86

With the standing wave reflectometer connected to a wire and the shield, larger length measurements were indicated. In fact, the measurements shown in Table 8 were larger than those for the cable while it was part of the longer assembly as shown in Table 6. Accurate measurements of the single cable with an open circuit could be obtained if the relative velocity in the tester were reduced from 0.45 to 0.41 and while the tester impedance settings were in the range 50 - 200 Ω. A lesser reduction in the instrument relative velocity setting would seem to be required for the impedance setting of 400 Ω although these readings also showed greater variation.

Even longer length measurements were obtained for the cable terminated in a short circuit. Of course this can be rectified by changing the setting of the relative velocity in the tester. As the same characteristic impedance should be expected for short circuit and open circuit configurations, however, an instrumental inaccuracy seems to exist in one or both length measurements. In practice, the accuracy of the measurement is directly related to the accuracy of the estimated relative velocity and with it the related wavelength as shown in Equations (6 & 7).

Table 8. Tests for the standing wave reflectometer connected to one wire and the shield of a cable comprising three wires within a shield. Length of the cable was 3.84 m. Relative velocity setting was 0.45.

Impedance Setting (Ω)	Termination	Detected Termination	Length to Termination (Foot.inch)	(m)
20	Open Circuit	No Fault Found	-	-
50	Open Circuit	Open Circuit	13.11	4.24
100	Open Circuit	Open Circuit	13.11	4.24
200	Open Circuit	Open Circuit	13.11	4.24
400	Open Circuit	Open Circuit	12.11± 0.2	3.94
20	Short Circuit	No Fault Found	-	-
50	Short Circuit	No Fault Found	-	-
100	Short Circuit	Short Circuit	14.10	4.52
200	Short Circuit	Short Circuit	14.10	4.52
400	Short Circuit	Short Circuit	14.9	4.49

3.4 Measurements on a Twisted Pair of Wires

A twisted pair that formed part of a wire loom was traced to a terminal post where two separate wires continued a short distance. The twisted pair was marked M27500 – 20ML2U)) 05973. This was identified as an unshielded twisted pair of 20 gauge wires designed to the MIL-W-81044/12 standard. The insulation for this wire was crosslinked polyalkene. The length of the twisted pair was 4 m ± 100 mm with the relatively large uncertainty due to the difficulty of tracking the wire in the loom. The length of the two individual lead wires connected to the terminal posts was 650 mm. The standing wave reflectometer was set to a relative velocity of 0.66, and for a range of set resistance values, tests were made on the twisted pair/lead combination with a combined length of 4.65 m. The results for open circuit and short circuit wires are shown in Table 9.

The measurements showed good accuracy for open circuit tests over the entire range of impedance settings. The measurements on short circuit twisted pair cable showed good repeatability for the full range of impedance settings but exhibited an error of approximately 10 %.

Table 9. Tests for the standing wave reflectometer on an unshielded twisted pair in a loom and connected to two individual wires at a terminal post. Length of the combined cables was 4.65 m. Relative velocity setting was 0.66.

Impedance Setting (Ω)	Termination	Detected Termination	Length to Termination (Foot.inch)	(m)
20	Open Circuit	Open Circuit	15.3	4.65
50	Open Circuit	Open Circuit	15.3	4.65
100	Open Circuit	Open Circuit	15.3	4.65
200	Open Circuit	Open Circuit	15.3	4.65
400	Open Circuit	Open Circuit	15.3	4.65
20	Short Circuit	Short Circuit	16.10	5.13
50	Short Circuit	Short Circuit	16.10	5.13
100	Short Circuit	Short Circuit	16.10	5.13
200	Short Circuit	Short Circuit	16.10	5.13
400	Short Circuit	Short Circuit	16.10	5.13

3.5 Measurement on Two Wires in a Loom

Two wires with a common source and destination were tested both with the remote end open circuit and short circuit. The two wires were connected via bared conductors to the standing wave reflectometer. The path of the two wires included connectors in two distribution panels with a total length of 5.40 m. The relative velocity was set at 0.6, the upper level of the range 0f 0.5 – 0.6 recommended by the Operating Guide. Repeatable and acceptably accurate results were obtained for each configuration for the whole range of impedance settings. The results are shown in Table 10. The values for the short circuit configuration are significantly larger than the open circuit readings.

Table 10. Tests for the standing wave reflectometer on two adjacent wires within a loom which pass through connectors at two distribution panels to common equipment. Length of the combined cables was 5.40 m. Relative velocity setting was 0.60.

Impedance Setting (Ω)	Termination	Detected Termination	Length to Termination (Foot.inch)	(m)
20	Open Circuit	Open Circuit	18.3	5.56
50	Open Circuit	Open Circuit	18.3	5.56
100	Open Circuit	Open Circuit	18.3	5.56
200	Open Circuit	Open Circuit	18.3	5.56
400	Open Circuit	Open Circuit	18.3	5.56
20	Short Circuit	Short Circuit	19.4	5.89
50	Short Circuit	Short Circuit	19.4	5.89
100	Short Circuit	Short Circuit	19.4	5.89
200	Short Circuit	Short Circuit	19.4	5.89
400	Short Circuit	Short Circuit	19.4	5.89

4. Summation

The ESP standing wave reflectometer utilises reflection at the remote end of a two conductor transmission line to detect a fault and a distance to the fault.

The transmission line may be intentional, such as a coaxial cable or incidental such as a wire in a loom.

The ESP standing wave reflectometer provides one of three responses to the condition of a cable namely, open circuit, short circuit or no fault found.

An operator needs to set an impedance value and a relative velocity value before activating the standing wave reflectometer.

When the standing wave reflectometer detects a short circuit or an open circuit it also provides a distance to the fault which is acceptably accurate for a correct setting of relative velocity.

The distance to fault that is calculated is directly related to the relative velocity value that is set by the operator.

Since estimating the relative velocity is such an important factor for accurate operation, a test on a known length of similar cable for a short circuit and open circuit would be useful if this could be carried out. Given the large number of wire types in an aircraft a test cable may not be readily available so a better estimate may be more practical. In many cases a better estimate than is currently available may be feasible based on the insulation materials of various types of cables.

Some impedance values set by the operator during testing caused short circuits to be undetected, in which case the standing wave reflectometer gave a response of no fault found.

During testing of a cable terminated in a matched load, erroneous open circuit responses accompanied by greatly varying distance readings were sometimes recorded.

Aircraft cables are often interrupted by connectors and terminal posts. These have the propensity to influence standing wave reflectometer results.

5. Conclusions

The ESP standing wave reflectometer is an effective tool for determining the distance to a known short circuit or an open circuit.

The accuracy of the result depends on using a relative velocity setting which is appropriate for the cable under test.

More accurate estimates of the relative velocity for different wire constructions and insulation types is needed.

Some impedance settings can produce erroneous results when testing cables with a short circuit.

Intervening connectors or terminal post connections may bias the results for a particular electrical cable run.

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19. ABSTRACT

The Eclypse ESP standing wave reflectometer was tested for its ability to locate open and short circuits on pairs of electrical wires. The robust and simple to use hand-held device was shown to operate successfully and quickly on coaxial cables, twisted pairs, shielded cables and pairs of wires within multi-wire looms. For aircraft wire management this offers an improved fault location capability prior to repairs on the flight line or during maintenance. The ESP could also find application in other defence platforms with complex electrical wiring.

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